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Implications of biomass pretreatment to cost and carbon emissions: Case study of rice straw and Pennisetum in Taiwan

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ABSTRACT

The purpose of this study was to explore the impact of feedstock collection and torrefaction pretreatment on the efficiency of a biomass co-firing system. Considering the transformation of existing municipal solid waste incinerators, several scenarios in which biomass supply chains depend on centralised pretreatment and transportation alternatives are presented. The cost, net energy output, and greenhouse gas effects of these scenarios were analysed using a spreadsheet model. Based on the Taoyuan County case in Taiwan, the mitigation costs of carbon emissions for rice straw and Pennisetum are 77.0 \$/Mg CO_2 and 63.8 \$/Mg CO_2, respectively. Results indicate that transporting feedstock from its source to the pretreatment and co-firing stations contributes the most to logistical costs for both straw and Pennisetum, regardless of whether torrefaction was adopted. Nonetheless, torrefaction requires more demonstrated cases at various scales to obtain the technical and economic data required for further analysis.

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1. Introduction

Agricultural residues and energy crops grown on degraded lands are considered sustainable sources of biomass energy because they do not impinge on the land currently used for food and feed production (Shie et al., 2011; Sims et al., 2010); however, they often involve materials with a variety of chemical compositions and low energy densities, which limit their utilisation in biomass conversion (Zhu et al., 2011). These characteristics increase the burden of transportation and follow-up refinement, making logistics complex and expensive. These challenges have necessitated the development of a biomass pretreatment technology to homogenise the raw materials and improve their energy density (Somerville et al., 2010).

Torrefaction is used to convert diverse biomass feedstock into an energy dense homogeneous solid. It is a mild prepyrolysis process performed at 200–300 °C in the absence of oxygen with a typical time period of 1 h (Bergman et al., 2005; Phanphanich and Mani, 2011). Pentananunt et al. (1990) first suggested using torrefaction to increase the combustion efficiency of wood. Since then, with the increased need for effective utilisation of biomass, torrefaction pretreatment has been investigated on a wide range of biomass feedstock. For example, the Energy Research Center of the Netherlands (ECN) conducted a series of studies to explore the underlying mechanism of torrefaction for wood chips. In ECN, Bergman et al. (2005) indicated that biomass torrefaction on the basis of mass can attain an energy densification efficiency of 1.3 (Boerrigter et al., 2006). The initial energy density of conventional wood pellets (8–11 GJ/m^3) increased to 15–18.5 GJ/m^3 following torrefaction, thereby reducing logistical costs by more than 50% (EverGreen Renewable, LLC., 2009).

For herbaceous biomass, Bridgeman et al. (2008) used willow, reed canary grass, and straw as feedstock for torrefaction, and the results indicated that both volatile and char combustion of the torrefied sample become more exothermic compared to the raw fuels. Uslu et al. (2008) discussed the economic effects of torrefaction and torrefaction plus pelletisation (TOP). The study used energy crops grown in Latin America as the source of biomass and transferred it to Western Europe for conversion following several pretreatment processes. According to their results, production costs for fuel from TOP are comparable to current gasoline and diesel production cost depending on the market. Therefore, the authors concluded that well-designed supply chains make international trade of biomass feasible from an energy efficiency and economic perspective.

Most of the raw materials of biomass such as crop and forest residues are scattered over a wide geographical area, making it difficult to collect such materials for utilisation (Sims et al., 2010; Zhu et al., 2011). Several studies (Sokhansanj et al., 2006; Tatsiopoulos and Tolis, 2003) have proposed specific biomass supply chains to obtain more efficient logistical operations leading to critical cost reductions considering time schedule, geological condition, equipment throughput, storage and pretreatment efficiency. Tatsiopoulos and Tolis (2003) studied the use of cotton stalk for electricity generation and in a combined heat and power

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Nomenclature

C_F	fuel cost per field hour ($ h^{-1})
C_I	interest of equipment purchase per field hour ($ h^{-1})
C_L	labor cost per equipment hour ($ h^{-1})
C_M	cost of equipment purchase per field hour ($ h^{-1})
C_R	cost of equipment maintenance per field hour ($ h^{-1})
C_T	transportation cost ($ (metric ton)$^{-1}$)
D	retail price of diesel ($ L^{-1})
D_d	rate of fuel consumption (L (kW h)$^{-1}$)
E_{CO_2}	emission of carbon dioxide (kg CO_2 (metric ton)$^{-1}$)
E_i	energy use (MJ (metric ton)$^{-1}$)
E_o	net energy generation (MJ (metric ton)$^{-1}$)
E_r	reduction amount of carbon dioxide emission (kg CO_2 (metric ton)$^{-1}$)
F	fuel cost per equipment hour ($ h^{-1})
Ft	fuel tax ($ L^{-1})
h	annual equipment operational hour (h yr^{-1})
i	annual interest rate (decimal fraction)
k	sum of taxes of equipment (%)
K	transportation distance (km)
M_e	efficiency of equipment operation (metric ton h^{-1})
n	expected life of equipment of building (yr)
N	number of operational staff (person)
P	purchase price of the equipment ($)
Q	wage in field hour ($ h^{-1})
Q_{truck}	wage of truck drivers ($ h^{-1})
r	electricity sold rate ($ (MJ)$^{-1}$)
R	profit of power generation ($ metric ton^{-1})
S	salvage value ($)
T	power of the equipment (kW)
W	load of truck (metric ton)
α	the ratio of equipment operational time and field operational time (equipment hour/field hour) (decimal fraction)
β	operation efficiency (field hour/equipment hour) (decimal fraction)
η	efficiency of power generation (decimal fraction)

co-generation system in Thessaly, Greece. The authors used linear programming to optimise costs incurred by various steps in the logistics system and showed that economies of scale can be achieved as the transport-vehicle capacities rise and a minimum biomass price can be achieved if the number of CHP units installed lies in a suitable range. Sokhansanj et al. (2006) developed an integrated biomass supply and logistics model (IBSAL) to simulate the flow of materials from the original biomass location to the refineries, while also considering pollution and energy investment. They collected data on weather statistics, biomass production, and the efficiency of machines, and IBSAL was used to calculate fixed and variables costs. The IBSAL model has been further utilized to characterise the impact factors on cost of biomass logistics such as those for granulated switchgrass and pelleting treatments (Sokhansanj and Fenton, 2006). The largest factors affecting overall cost of delivery of biomass are bulk density of the biomass, moisture content, and transportation distance (Sokhansanj and Fenton, 2006). Rentizelas et al. (2009) assumed the use of multiple types of biomass materials and three forms of energy (electricity, heating, and cooling) to establish a biomass supply chain and to develop a decision support system from the perspective of investors. Through hybrid optimisation methods, the economic effects of non-linear systems were evaluated.

The location of pretreatment facilities is crucial for the logistics of biomass energy systems, and geographic information systems (GIS) have been used to select optimal locations for pretreatment or conversion facilities based on the spatial distribution of biomass (Leduc et al., 2010; Tittmann et al., 2010). However, land in those locations was often difficult to acquire (Environmental Protection Administration, 2008a). In the 1990s, Taiwan began building municipal solid waste incinerators for each county (Huang et al., 2006). With recent reductions in garbage through source separation measures (Tsai and Chou, 2006), many incinerators have reported excess capacity, and many plan to shut down. Consequently, the Taiwan Environmental Protection Administration plans to use existing incinerator locations and reuse some of the existing equipment for biomass pretreatment processes (Environmental Protection Administration, 2008a; Tsai, 2009). Since incinerators own surplus treatment capacities caused by successful refuse reduce/reuse/recycle (3R) programs, agriculture residues such as rice straw has been directly co-fired at several waste-to-energy incinerators to generate electricity with neutral carbon emission. Straw can be processed with the reception equipment of incinerators, and existing storage pits can be partitioned to store straw which will be handled by in situ overhead cranes. If new biomass pretreatment (torrefaction) facilities can be stationed near incinerators and if auxiliary conveyors are added to connect the existing storage pits to new feeding bunkers/silos for the torrefaction process, torrefaction facilities can take advantage of saving space and investment for separate biomass storage requirements.

Most studies on biomass logistics have focused on the reduction of costs for specific feedstocks in specific areas by innovative pre-treatment processes or mathematical optimisation models. When countries desire to promote the production of biomass energy, surveys of biomass logistics aimed at local feedstocks are crucial, and geographic characteristics of biomass sources and potential types and locations of biomass utilisation should be included in the initial survey. Although findings from previous studies are relevant to the transformation of Taiwan's existing incineration plants to biomass energy centres, more work is needed to explore actual feedstock distribution and feasibility of centralised pretreatment in the biomass energy centres. To illustrate the potential effects on biomass utilisation and incinerator transformation, this study investigated the distribution of raw material, torrefaction pretreatment, and storage near an existing incineration plant. Four biomass supply chain scenarios were designed in which logistical costs, carbon emissions, and net energy generation of rice straw (an agricultural residue) and Pennisetum (an energy crop) were modelled.

2. Methods

Rice straw and Pennisetum were selected as examples of agricultural residues and energy crops, respectively. An existing municipal waste incinerator was assumed as biomass energy center. Several scenarios of biomass-to-energy chains were designed, depending on whether torrefaction was applied as a pretreatment and whether biomass would be transferred to the biomass energy centre before being transported to the power plant for co-firing. The economic evaluation of the scenarios included the purchase of biomass materials, harvesting and collection, torrefaction pretreatment (if applied), transport to the pretreatment centre (if applied), and transport to the power plant. Assuming each step was an independent unit, mass yields, energy yields, costs, and carbon emissions were evaluated by developing a spreadsheet model to determine energy and the mass flow, capital costs, and benefits of reducing carbon emissions. Taoyuan County, the main area of rice production in northern Taiwan, was selected as the study area to demonstrate the designated scenarios.

2.1. Torrefaction technology

Torrefaction is a pretreatment technology used to make biomass more suitable for co-firing applications. Even though torrefaction is a technology that is not commercially available, several pilot-scale tests have indicated that torrefaction is feasible from an energy efficiency perspective (Uslu et al., 2008; Bridgeman et al., 2008). According to Bergman et al. (2005), a thermal process efficiency of typically 96% is to be expected and a net process efficiency of 92% (including electricity consumption) under the favored conditions. The present study adopted torrefaction equipment used by Agri-Tech Producers (Agri-Tech Producers, 2011) with a processing capability of 5 Mg/h. The estimated consumption of electricity is 225 kW, and gas is 200,000 BTU/h.

The torrefaction process (shown in Fig. A1) includes sizing (<4 cm), drying (<40% moisture content), adding nitrogen gas, slow-heating (rate of temperature increase <50 °C/min) of the system to 250–300 °C and densifying (>0.500 kg m^{-3}). Through torrefaction, the biomass is decomposed and completely dehydrated (<3% moisture content). Biomass will be directly torrefied and then pelletized to increase the bulk density. Since torrefied biomass is brittle and of low mechanical strength, it is easily pulverised alongside coal in the power plant.

The mass and energy balance for rice straw and Pennisetum torrefaction has been calculated based on proximate analysis (Figs. A-2 and A-3 in the supplementary data). Prior to torrefaction, the lower heating value ($LHV_{a.r.}$) of rice straw is 15.07 MJ/kg; after torrefaction treatment at 250 °C, the $LHV_{a.r.}$ increases to 16.90 MJ/kg. The $LHV_{a.r.}$ of Pennisetum before and after torrefaction were assumed to be 2.85 MJ/kg and 15.69 MJ/kg, respectively according to results obtained for microwave-induced torrefaction of rice straw and Pennisetum (Chen et al., 2011).

Since specific cost data related to torrefaction pretreatment have not been reported, a set cost of \$14.8 Mg^{-1} for all scenarios involving straw was assumed based on the cost model for torrefaction of cellulosic biomass proposed by Maski et al. (2010) (15% moisture content, medium level capital cost). Since the moisture content of Pennisetum was high relative to rice straw, the cost for torrefaction of Pennisetum was set at \$32.0/Mg based on the same cost model, using a 60% moisture content, and medium level capital cost datum.

2.2. Scenarios of supply chains

Fig. 1 outlines the supply chain scenarios. In scenario 1–1, biomass was transported to a biomass energy centre and then transported to the power plant without torrefaction treatment. In scenario 2–1, biomass was transported to the biomass energy centre and torrefaction and then transported to the power plant. In scenario 1–2, the biomass was not transported to the biomass energy centre and was not treated using torrefaction; it was directly transported to the power plant. In scenario 2–2, the biomass was not transported to the biomass energy centre but was pretreated using torrefaction at the centric position of feedstock fields of each district in Taoyuan County and directly transported to the power plant.

2.3. Optimisation of transportation routes

In adopting the results of the land use investigation from the National Land Surveying and Mapping Center (Ministry of the Interior Taiwan), this study used GIS to determine the straw supply area and uncultivated fields that could be used to grow

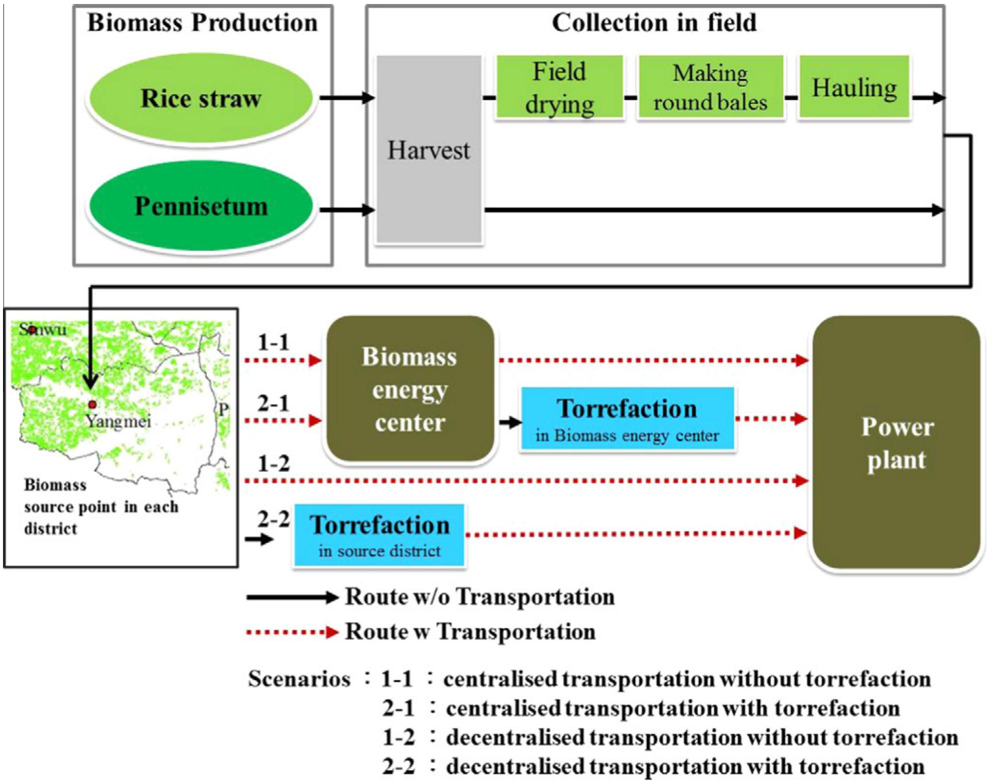

Biomass Production
Rice straw
Pennisetum
Collection in field
Harvest
Field drying
Making round bales
Hauling
Sinwu
Yangmei
P
Biomass source point in each district
1-1
2-1
1-2
2-2
Biomass energy center
Torrefaction in Biomass energy center
Torrefaction in source district
Power plant
Route w/o Transportation
Route w Transportation
Scenarios : 1-1 : centralised transportation without torrefaction
2-1 : centralised transportation with torrefaction
1-2 : decentralised transportation without torrefaction
2-2 : decentralised transportation with torrefaction

Fig. 1. Scenarios of biomass supply chains.

Pennisetum. Geometric calculation by GIS was used to determine the centroid position of the biomass supply area in each district of Taoyuan County, and these locations were used as biomass source points. Next, the Network Analyst module of ESRI ArcGIS was used to determine the optimal transportation route with the lowest cost by establishing road attributes and driving limits (80 km/h for freeway and 40 km/h for other roads). U-turns were forbidden and one-way rules were to be followed.

2.4. Cost analysis

The costs of raw materials, harvest and collection, pretreatment, transportation and power generation were analysed. Feedstock properties are listed in Table 1. Values were converted to US dollars when local cost data were used. The purchase cost for straw from farmers was set at $22 Mg^{-1} straw and planting costs were $6.3 Mg^{-1} for Pennisetum according to market prices in Taiwan. When compared to costs reported in the literature (Jenkins et al., 2000; Samson et al., 2001), these costs were lower. It is assumed that nutrient replacement for removing the biomass from the field was included in the straw purchasing prices, but the energy and carbon emission related to the nutrient manufacturing and transportation were ignored due to too complicated source conditions.

2.4.1. Cost of harvest and collection

The cost of biomass harvest and collection was separated into fixed and variable costs. Fixed costs included equipment purchases (C_M) and interest (C_I), while variable costs included maintenance costs (C_R), fuel usage (C_F), and labour (C_L). Based on data reported by Sokhansanj et al. (2006) and local equipment information, each cost was analysed using spreadsheets. C_M was the cost of equipment purchases ($/field hour)

$$C_M = \alpha \cdot \left\{ \left[p - \frac{S}{(1+i)^n} \right] \frac{i(1+i)^n}{(1+i)^n - 1} + \frac{Si}{(1+i)^n} \right\} \Big/ h \tag{1}$$

where P is the present value cost of equipment purchase, S is the salvage value of the equipment by the end of the period, i is the annual interest rate or discount rate, n is the number of periods, α is the ratio of equipment operational time to field operational time (equipment hour/field hour), and h is the annual equipment operational hour (h/year).

C_I is the interest of the equipment ($/field hour) and is equal to the opportunity cost of the equipment purchase, equipment maintenance, and fuel consumption (the inability to use such resources in other investments or production opportunities)

$$C_I = \alpha \cdot \left[k \frac{(p+s)}{2} + \frac{i}{2}(C_R + C_F) \right] \Big/ h \tag{2}$$

where k is the sum of the rates of taxes on the equipment, C_R is the cost of equipment maintenance, and C_F is the cost of fuel consumption. C_R is the cost of equipment maintenance ($/field hour), which is equal to 55% of the present value of the equipment (Environmental Protection Administration, 2008b). After distributing C_R to the average life expectancy of the equipment, the following equation is obtained

$$C_R = \alpha \cdot \left(\frac{0.55P}{n} \right) \Big/ h \tag{3}$$

C_F is the cost of fuel consumption ($/field hour), including both fuel (diesel) and lubricant (15% of fuel cost)

$$C_F = \alpha \cdot (1 + 0.15) \cdot F \tag{4}$$

where F is the cost of fuel ($/equipment hour) obtained by multiplying the fuel consumption rate of the diesel engine (D_d, Table 2), the diesel price (Table 2) and the engine power of harvest and collection equipments (Table A-1 of the supplemental data). C_L is the cost of labour ($/equipment hour)

$$C_L = \beta \cdot (1.3QN) \tag{5}$$

where Q is the wage ($/field hour), N is the number of operational staff members, the profit is set at 30%, and α is operation efficiency (field hour/equipment hour). Truck operation costs included transport wages (Q_{truck}), profit, and the number of drivers. The information of equipments size and price for harvest and collection used in this study is available in supplemental Table A-1.

2.4.2. Storage cost

Biomass storage was assumed to take place in the biomass centroid of each district. A cost of $3.80 Mg^{-1} for storage of rice straw in a center pole-supported gravel pad metal building was adopted (Jenkins et al., 2000). The cost for in-field grower storage and storage in the biomass energy center are ignored because they take the advantage of utilising the existing facilities.

Table 2
Main parameters used for economic analysis.

Parameter[a]	Value	
i	4.776	%
n	10	yr
α	1.1	
β	1.2	
k	2	%
D_d	0.265	L (kWh)$^{-1}$
D	0.68	$ L^{-1}
F_t	0.05	$ L^{-1}
h	720	$ h yr^{-1}
Q	3.84	$ h^{-1}
Q_{truck}	3.84	$ h^{-1}

[a] see Nomenclature.

Table 1
Feedstock properties.

	Raw rice straw[a]	Torrefied rice straw[b]	Raw Pennisetum[c]	Torrefied Pennisetum[b]
Moisture (%)	15	3	70	3
Bulk density (kg/m^3)	182	500[d]	426	500[d]
Size (cm)	Small round bale D: 40–50 H: 80–110	–	Direct-cut 2–4	–
LHV$_{a.r.}$ (MJ/kg)	15.07	16.90	3.66	15.69

[a] The raw type information for rice straw were obtained from a survey of field conditions conducted by Taiwan EPA (2008b).

[b] The properties for torrefied materials were from Chen et al. (2011). A microwave-induced torrefaction experiment of rice straw and Pennisetum was conducted in their research, but the raw materials of their experiment were with lower moisture content (5.3% for both rice straw and Pennisetum).

[c] The data of raw Pennisetum were considered similar to the silage harvest for herbaceous crops (Turhollow et al., 1996).

[d] Estimated by this study. A range from 380 to 500 kg/m^3 was indicated in the Bergman et al. (2005).

2.4.3. Transportation cost

Transportation cost, C_T (\$/Mg), is related to transportation distance and truck cargo capacity

$$C_T = \frac{(D + F_t) \cdot K}{3.7 \cdot W} \tag{6}$$

where D and F_t are the retail price of diesel and fuel tax (\$/L), respectively, K (km) is the transportation distance, and W (Mg) is the load. The average fuel consumption of a truck weighing 3.5 tons or above is 3.7 km/L (Environmental Protection Administration, 2008b).

2.4.4. Efficiency of agricultural equipment

Information regarding the efficiency of the agricultural equipment is provided in supplemental Table A-1. The cut straw was left in the fields for 2–3 weeks before it was packed to decrease its moisture content to 15% and to allow drying of the soil for entry of collection equipment.

Straw bales (Table 1) were collected using a straw-collecting device attached to tractors that acted as the power source. Packed straw was then stacked manually, and vehicles were used to move the bales to the warehouse.

Pennisetum involves a vertical tall-stem pasture and was collected using a harvester connected to transportation vehicles, which acted as power sources. Following cutting, rotating blowpipes were used to blow the Pennisetum into the loader, thus requiring no manual labour. The Pennisetum (Table 1) contained approximately 70% moisture, but was dense and hard and could therefore be transported immediately after harvesting without packing (Turhollow et al., 1996). Due to the expensive nature of drying thick-stemmed crops such as Pennisetum, drying was not considered before torrefaction during all the logistical scenarios. Wet storage results in lower harvesting costs, lower dry matter loss during storage, increased product uniformity and a reduced risk of fire.

2.5. Energy use and carbon dioxide emissions

When collecting biomass, field operation equipment and vehicles used diesel; therefore, energy use E_i (MJ/Mg) and carbon dioxide emissions E_{CO_2} (kg CO_2/Mg) are calculated using the following equations

$$E_i = (38.7 D_d T)/M_e \tag{7}$$

$$E_{CO_2} = (2.73 D_d T)/M_e \tag{8}$$

where D_d is the rate of fuel consumption (L/kWh), T is the power of the equipment (kW), M_e is the efficiency of operating capacity of the equipment (Mg/hour), diesel energy density is 38.7 MJ/L, and the diesel carbon emission coefficient is 2.73 kg CO_2/L (MOEA, 2008). The emission of carbon dioxide by the torrefaction equipment was calculated using power consumption, in the form of electricity and natural gas emission factors (0.186 kg CO_2/MJ and 0.052 kg CO_2/MJ) (MOEA, 2008).

2.6. Profit of power generation, net energy production, and reductions in carbon dioxide emissions

The profit of power generation, R (\$/Mg), is equal to the difference between the revenue of electricity sales and total costs.

$$R = revenue\ of\ electricity\ sales\ -\ logistics\ cost\ -\ power\ generation\ cost$$

$$R = r\eta E - \left(\sum \left(\frac{C_M + C_I + C_R + C_F}{\alpha M_e} + \frac{C_L}{M_e} \right) + C_T \right) - 26.9 \tag{9}$$

where γ is the rate at which electricity was sold (using the rate of biomass power at the renewable energy wholesale rate in Taiwan, 17.8 \$/GJ), γ is the efficiency of power generation (5–40%), and E is the lower heating value of biomass (MJ/Mg). The total cost of biomass utilisation is the sum of the logistics costs and cost of power generation. For power generation cost, the value reported in the Zhang et al. (2009) for co-firing station in Canada (30 \$/MWh) was used as an estimate, at 10% wood pellet co-firing with coal and assuming the heating value as fired of 24 GJ/Mg.

Net energy production, E_o (MJ/Mg), is determined by subtracting the total amount of power generated from the energy consumption of all equipment and transportation vehicles

$$E_o = \eta E - \sum E_i \tag{10}$$

It was assumed in this study that the amount of carbon dioxide emitted during electricity generation via biomass combustion was equal to the amount of carbon dioxide absorbed through photosynthesis, thus yielding a carbon neutral process. Therefore, the reduction in carbon emissions as a result of a partial replacement of coal by biomass equaled the net profit of carbon emissions reduction. E_r is equal to the reduction in carbon dioxide emissions (kg CO_2/Mg)

$$E_r = 0.186 \eta E - \sum E_{CO_2} \tag{11}$$

The values of parameters are shown in Table 2.

3. Results and discussion

3.1. Geographical distribution of biomass

From the analysis of the national land use database by GIS, the area of rice fields in Taoyuan County accounted for 17,979 ha. Assuming each hectare yielded 6 tons of straw and 30% of straw was used in the areas as cover to suppress weed growth, or as fertilizer, a total of 75,342 tons of straw could be used as biomass feedstock every year.

The total area of uncultivated fields in Taoyuan County was 1224 ha, and it was assumed that these fields could be used to grow Pennisetum as the feedstock for bioelectricity. Annually, 50–75 Mg/ha of Pennisetum (dry basis) could be produced, yielding, on average, 59,323 tons per year.

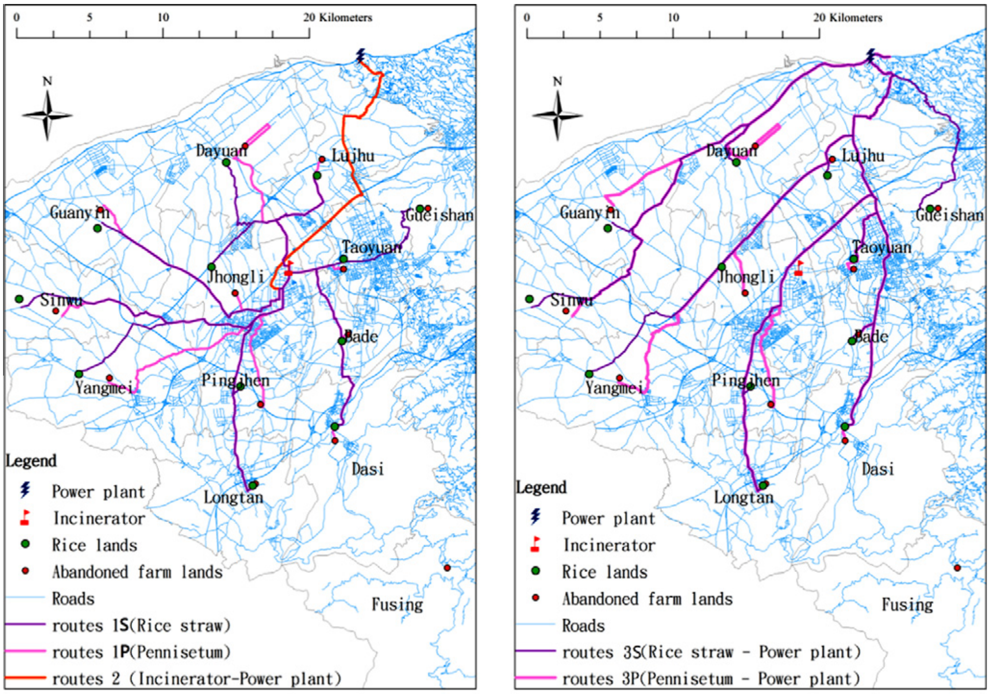
3.2. Optimisation of transportation routes

The optimised transportation routes obtained using GIS are shown in Fig. 2. During route planning, a centralised and decentralised route was designed. The centralised route was used when biomass was transported to the biomass energy centre for temporary storage and torrefaction (if applied) and then to the power plant. From each original source to the biomass energy centre, the shortest paths were denoted as 1S for straw (4.2–22.7 km) and 1P for Pennisetum (4.2–20.0 km), and the shortest path from the biomass energy centre to the power plant was route 2 (24.5 km). The shortest decentralised paths (directly from the biomass sources to the power plant) were denoted as route 3S (12.7–38.0 km) for straw and 3P (12.2–38.2 km) for Pennisetum. Locations for decentralised torrefaction facilities were assumed to influence only operational and transportation costs and not to influence the planning of transportation routes.

3.3. Cost analysis

3.3.1. Cost of raw materials, harvest, collection, storage and pretreatment

The costs of materials, harvest and collection, storage and pretreatment of straw and Pennisetum are shown in Table 3. The operational costs of tractors and trucks contributed the most to



(a) Centralised (b) Decentralised

Fig. 2. Optimised transportation routes for (a) centralised and (b) decentralised scenarios.

the cost of field operations for straw and Pennisetum, respectively. Because the purchase cost of materials involved buying straw from farmers or planting Pennisetum, it varied seasonally and was considered a highly uncertain variable. Moreover, because torrefaction pretreatment largely remains a new technology, these costs have not been well investigated and require more field data for verification.

3.3.2. Transportation cost

Transportation costs for both biomass species were much higher than field collection costs, as shown in Tables 3 and 4. For rice straw, as the distance from the biomass energy centre to the power plant was relatively short (24.5 km), the benefit of the higher energy density of torrefied biomass was not obvious. Therefore, transportation costs in scenarios 1–1 and 2–1 were quite similar (36.07 and 33.82 $/Mg). Although biomass was transported directly to the power plant in scenarios 1–2 and 2–2, the distances varied between 12.2 km and 38.2 km, and thus, the transportation costs differed drastically between the two scenarios (60.32 and 31.97 $/Mg). The order of transportation cost for the scenarios was 1–2 > 1–1 > 2–1 > 2–2. The centralised torrefaction scenario was the cheapest. The results of Pennisetum transportation were the same.

3.3.3. Total cost

Combining the costs associated with material purchases, field operation, storage, torrefaction (if applied), and transportation, from highest to lowest total cost, resulted in the following order for rice straw: scenario 1–2 > 2–1 > 1–1 > 2–2 (Table 4). This means that the scenario where torrefaction was not used and biomass was not centralised to the biomass energy centre cost the most and the scenario in which torrefaction was adapted but biomass was transported to the biomass energy centre cost the least. The order of total cost was different from that of transportation due to the cost of torrefaction. The total cost of centralised transportation without torrefaction was lower than the cost of centralised transportation including torrefaction.

Table 3
Cost data of materials, harvest and collection, storage, and pretreatment (Unit: $/dry Mg).

Biomass	Material	Harvest and collection		Storage	Torrefaction
Rice Straw[a]	22[b]	Tractor	11.54	3.8[d]	14.7[e]
		Baler	1.05		
		Handler	7.55		
		Truck	1.85		
		Subtotal[c]	21.99		
Pennisetum[a]	6.3[f]	Harvest	1.68	3.8[h]	32[e]
		Truck	5.05		
		Subtotal[g]	6.73		

[a] The cost analysis based on 15% moisture content for rice straw and 70% for Pennisetum.

[b] Market price in Taiwan, nutrient replacement for removing the biomass from the field has been considered in the price paid to the growers.

[c] Source: Taiwan EPA (2008b) and Jenkins et al. (2000).

[d] Source: Jenkins et al. (2000). Metal buildings at the centroid position of the biomass supply area in each district were considered for this study.

[e] Source: Maski et al. (2010). Straw was based on the cost model of 15% moisture content, medium level capital cost and Pennisetum was set as $32.0/Mg based on the same cost model, using the 60% moisture content, medium level capital cost datum.

[f] Market price in Taiwan. A higher purchase price, US$ 38/ton (at 26% moisture) was estimated for utilising Pennisetum in the Philippines by Samson et al. (2001).

[g] Estimating follows the silage harvest process developed by Turhollow et al. (1996).

[h] It is assumed the storage cost may be similar to that of rice straw. Wet storage by ensiling the biomass is suggested (Li et al., 2011). Metal buildings at the centroid position of the biomass supply area in each district were also considered.

Due to a lack of information related to the cost of torrefaction technology, it was assumed that torrefaction costs were identical for both centralised and decentralised transportation. In fact, because the magnitude of pretreatment for centralised transportation was larger, the unit cost should be lower than the pretreat-

Table 4
Cost data related to transportation.

Material	Scenarios[a]	Distance 1 (km) Moisture content (%) Bulk density (kg/m^3)	Distance 2 (km) Moisture content (%) Bulk density (kg/m^3)	Transport cost ($/Mg)
Rice Straw	1–1	4.2–22.7	24.5	36.07
		15	15	
		182	182	
	1–2	12.7–38.0	0	60.32
		15	–	
		182	–	
	2–1	4.2–22.7	24.5	33.82
		15	3	
		182	500	
	2–2	12.7–38.0	0	31.97
		3	–	
		500	–	
Pennisetum	1–1	4.2–20.0	24.5	33.85
		70	70	
		426	426	
	1–2	12.2–38.2	0	58.32
		70	–	
		426	–	
	2–1	4.2–20.0	24.5	31.17
		70	3	
		426	500	
	2–2	12.2–38.2	0	25.66
		3	–	
		500	–	

[a] Scenarios: 1–1: centralised transportation without torrefaction, 1–2: decentralised transportation without torrefaction, 2–1: centralised transportation with torrefaction, 2–2: decentralised transportation with torrefaction.

ment for decentralised transportation. Moreover, although trucks with a larger load capacity were used to move the biomass to the power plant from the biomass energy centre, the purchase of additional transportation equipment also increases the cost of centralised transportation scenarios. Consequently, costs associated with decentralised transportation with torrefaction were the lowest due to the energy density of biomass already achieved in each district centroid.

The order for the Pennisetum scenarios was different from the straw scenarios. The total costs for decentralised transportation without torrefaction (1–2) and centralised transportation with torrefaction (2–1) are similar and higher than the other two scenarios. The centralised transportation without torrefaction scenario (1–1) was cheapest. This could be attributed to the high unit cost of torrefaction for Pennisetum which needs higher drying energy input. Regardless, the collection of Pennisetum was easier than that of straw and resulting in lower total cost than straw.

3.4. Energy use and carbon dioxide emissions

The comparison of energy use in Table 5 indicated that the energy use of scenario 1–2 (decentralised transportation without torrefaction) had the greatest energy use. This was because biomass was not pretreated by torrefaction or centralised transportation, which resulted in a lower energy density and lower transport capacity. This increased the amount of energy required to transport one energy unit of biomass and thus increased carbon dioxide emissions in the process.

3.5. Profit of power generation, net energy production and the reduction of carbon emissions

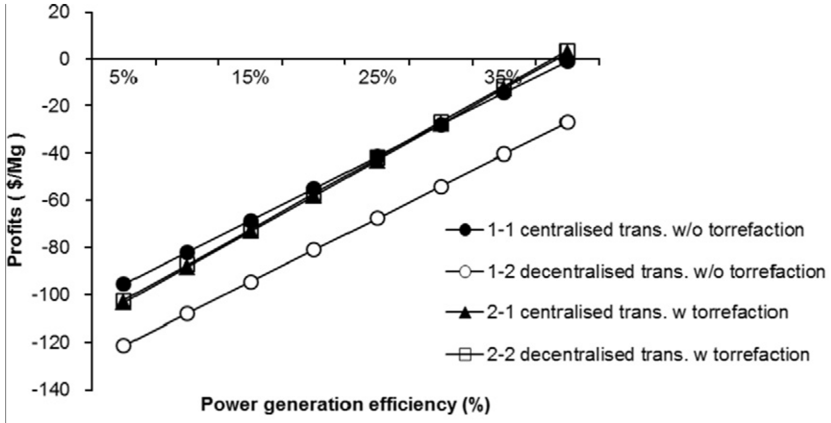
Fig. 3a presents the profits of straw under various schemes of power generation efficiency. The income generated from the sale of power increased with power generation efficiency. Under the current price of biomass power, profit was gained once efficiency reached about 38% for scenarios 2–2, 2–1 and 1–1, but no profits accumulated for scenarios with decentralised transportation or without torrefaction (scenarios 1–2). Typically, the highest power generation efficiency for combustion power plants is 40%. Therefore, coupling straw with power plants operating at full capacity and efficiency had a positive effect.

The analysis of profits using Pennisetum under various methods for power generation efficiency was identical to the method

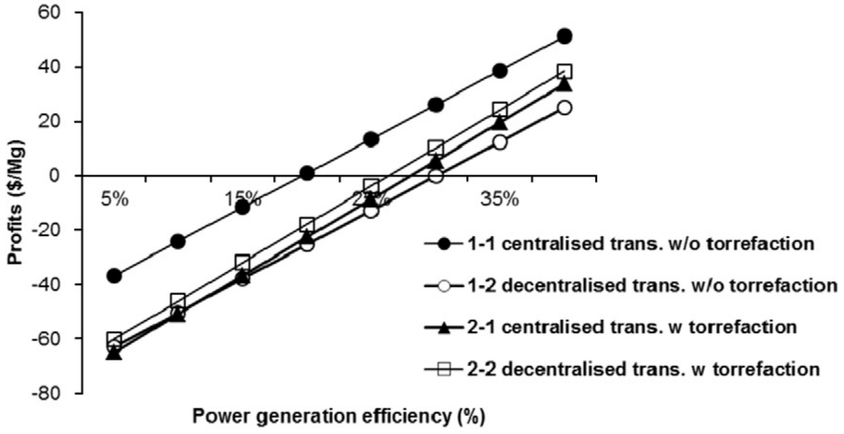
Table 5
Total cost, energy use and CO_2 emissions for scenarios.

Material	Scenarios[a]	Total cost ($/dry Mg)	Energy input (MJ/dry Mg)	CO_2 emission (kg CO_2/dry Mg)
Rice straw	1–1	82.2	2.31	163.09
	1–2	108.0	3.78	266.72
	2–1	90.9	2.39	162.50
	2–2	77.9	2.38	161.88
Pennisetum	1–2	49.1	1.83	129.13
	1–2	75.1	3.31	233.62
	2–1	74.9	2.16	132.82
	2–2	60.1	1.94	117.32

[a] Scenarios: 1–1: centralised transportation without torrefaction, 1–2: decentralised transportation without torrefaction, 2–1: centralised transportation with torrefaction, 2–2: decentralised transportation with torrefaction.



(a) Rice straw



(b) Pennisetum

Fig. 3. Profit from power generation using (a) rice straw and (b) Pennisetum under various levels of efficiency.

described above, and it was discovered that a scenario with centralised transportation but without torrefaction was profitable at 20% power generation efficiency. Under the other three scenarios, profitability was achieved at 30% efficiency (Fig. 3b). The reason for the different results could be due to the high moisture content of Pennisetum. The increase in heating value of biomass was limited after torrefaction pretreatment, and therefore, the benefits generated were not obvious.

Fig. 4 lists the net generation of energy from straw and Pennisetum (scenario 2–2). When power generation efficiency was 12% or higher, a net energy profit was produced for Pennisetum. For straw, an energy generation efficiency of 15% or higher generated a net energy profit. When the efficiency was more than 35%, the net energy production per unit dry Mg of rice straw and Pennisetum was almost the same. This result indicates that both may be promising biomass sources. Furthermore, in a combined cost analysis, the net energy cost-benefit ratio was used to compare the efficiency of straw and Pennisetum, as shown in Fig. 5. The cost-benefit of Pennisetum was higher than that of straw, and the difference increased as the efficiency of power generation increased.

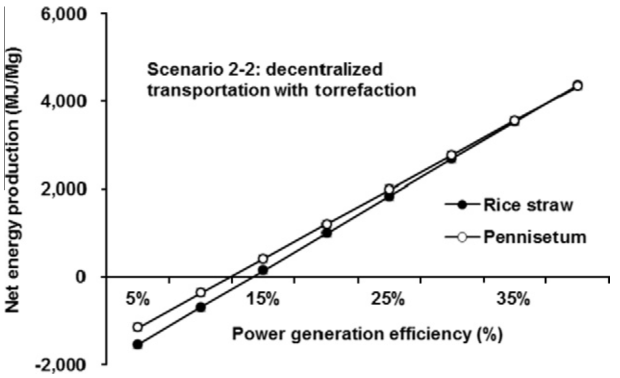


Fig. 4. Net generation of energy from rice straw and Pennisetum.

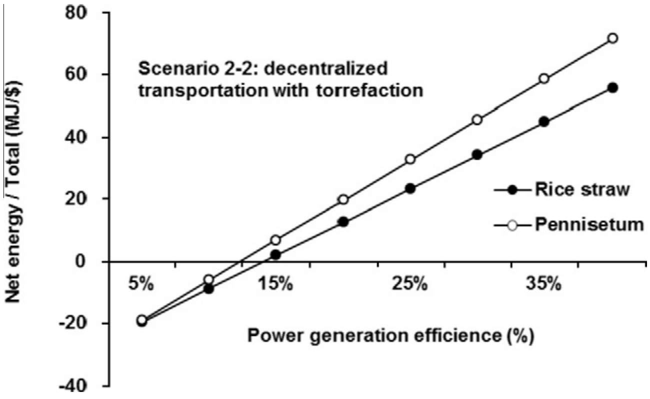
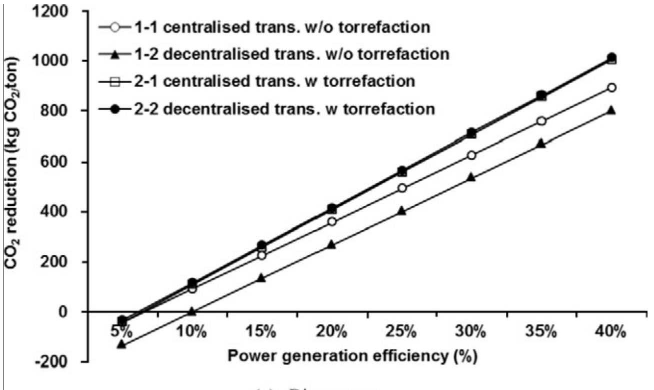
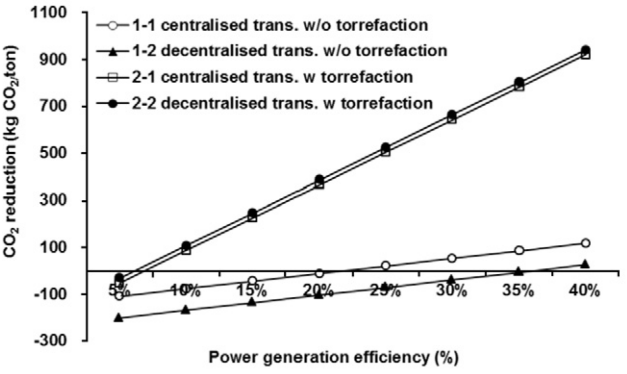


Fig. 5. Cost-benefit ratio of bio-energy for rice straw and Pennisetum.



(a) Rice straw



(b) Pennisetum

Fig. 6. Benefits of reduced carbon emissions from (a) rice straw and (b) Pennisetum with various levels of efficiency.

Fig. 6 illustrates the reductions in carbon dioxide emissions for straw and Pennisetum. The lowest reduction was obtained in scenario 1–2 (decentralised transportation without torrefaction). As torrefaction increased the heating value of biomass and centralised transportation increased the loading efficiency, power generation also increased. Consequently, the benefits of reduced carbon emissions for scenarios 2–1 and 2–2 were expected; however, when the benefits were presented as unit profit, the difference of two torrefaction scenarios was not obvious. For both straw and Pennisetum utilisation, the power generation efficiency for the four scenarios needed to be at least 10% to achieve carbon reduction. This indicates that when power generation efficiency was low, the generation of carbon emissions in the logistical operations exceeded the reduction of replacing coal combustion and increased emissions instead.

When the highest efficiency (40%) of power generation is assumed, the mitigation cost of carbon emissions for the rice straw in scenario 2–2 would be 77.0 \$/Mg of CO_2 equivalent and 63.8 \$/Mg for Pennisetum. The costs in the present study were considerably higher than those published by Zhang et al. (2009), primarily due to the high price of biomass (22 \$/Mg for straw) and torrefaction pretreatment. Assuming that waste rice straw required disposal if it was not used as biomass feedstock and a centralised scale-up torrefaction facility was available, a lower mitigation cost of carbon emission could be expected. Furthermore, carbon emissions during harvest and collection were all included in this study, and emissions would still exist, even if biomass conversion was not considered. Pennisetum grown in abandoned lands may also achieve the goal of installing a certain biomass-based electricity capacity for Taiwan (Tsai, 2009).

4. Conclusions

Waste straw and Pennisetum were used to determine the difference in the cost, energy balance, and benefits of reducing carbon emissions. Energy crops such as Pennisetum could be used to make up for feedstock shortages when agricultural residue is unavailable, but other energy crops with high heating value should be investigated. Furthermore, it is important to gather cost information on small-scale and centralised large-scale torrefaction to further explore the effectiveness of the centralised scenario. Although a biomass energy centre in Taiwan may be more complicated than what we discussed, the analytical methodology proposed in this research could help to optimise the supply chain in biomass utilisation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biortech.2012.01.006.

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